Profiling Hydrometeors from space using combined active and passive measurement techniques: A CloudSat Perspective

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1.0 Introduction

CloudSat is a multi-satellite, multi-sensor experiment designed to measure those properties of clouds considered critical for understanding the connections between clouds, weather and climate. The mission's primary science goal is to furnish data needed to evaluate and improve the way clouds are parameterized in global models, thereby contributing to better predictions of clouds and thus to the poorly understood cloud-climate feedback problem. As highlighted above, the key missing data to be provided include:

- vertical profiles of cloud occurrence
- vertical profiles of cloud liquid water
- vertical profiles of cloud ice water content
- precipitation (solid and liquid) occurrence in relation to the above
- cloud optical properties (when radar data are combined with other sensor data).

2.0 Measurement Approach

The approach developed to provide this information relies of the combination of measurements provided by a 94 GHz profiling cloud radar (CPR) and a spectrometer measuring reflected sunlight in the O_2 A-band region of the near-infrared spectrum (located between 760-770 nm, hereafter profiling A-band spectrometer, PABSI)

2.1 Radar Reflectivity Measurements

The radar receiver detects the power returned which is expressed as the radar reflectivity Z. This returned power is approximately proportional to the square of the water and ice content. An example of such information is provided in Fig. 1 showing a cross-section of Z measured using an airborne 94 GHz cloud radar flying over a complex-large scale cloud system. Key features of the physics of the clouds can be identified in reflectivity structures. One of the key properties of the CloudSat CPR is the minimum sensitivity of the instrument. This minimum is –28 dBZ which is many factors more sensitive than the TRMM radar for example and capable of observing very thin cirrus. A second factor of the radar design is the vertical resolution which is 500m.

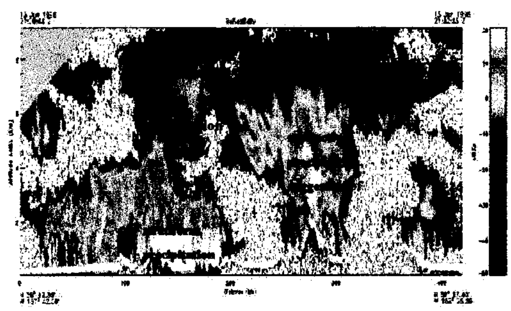


Fig. 1 An example of 94 GHz radar reflectivity measured from aircraft flying above and just within the top of a convective precipitating complex over Alaska.

2.2 Profiling capabilities from A-band measurements

The PABSI measurement concept is essentially portrayed in Fig. 2. PABSI measures the atmospheric radiance of the O_2 A-band rotational spectrum between 761.61 nm and 772.20 nm. The high spectral resolution is the key to measurement approach. Reflections at wavelengths outside the absorption line features arise from scatterings from the entire column. Reflections at wavelengths inside the stronger absorption lines arises from the upper levels. Therefore the penetration through the atmosphere and the ability to discriminate different scattering layers follows from the discrimination of reflection as a function of known variations in gaseous absorption. This discrimination is a consequence of the high spectral resolution measurements of PABSI (spectral resolution of 0.03 nm).

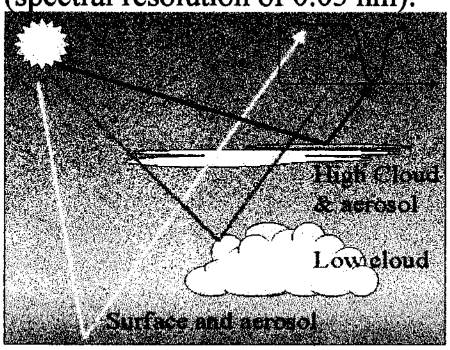
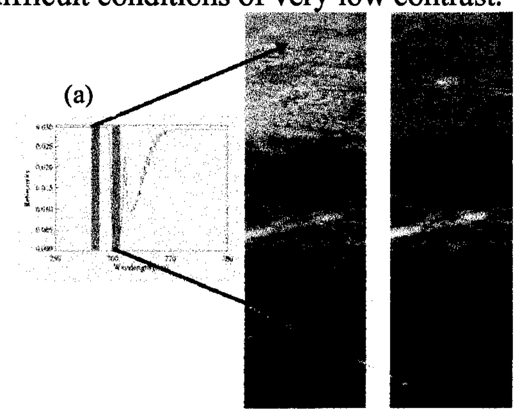
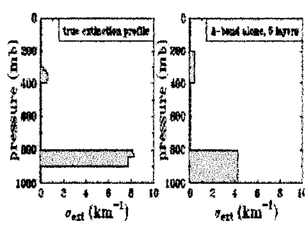


Fig. 2 The conceptual approach to the passive profiling of hydrometeors using reflected sunlight measured across absorption line features.

Figures 3a and b further convey this idea. Figure 3a shows images of cloud multiple layers of cloud derived from the MOS instrument. The image (left) corresponds to the image outside the absorption band analogous to most visible images of clouds. The image to the right corresponds to the same view but in the stronger portions of the A-band. A number of features that differ from one image to the other, notably how the larger cloud mass appears darker (because it is low in the atmosphere in the majority of the oxygen) whereas parches of high thin cloud appear bright. Figure 3b is an example of a retrieval of cloud properties using synthetic PABSI data. The scenario considered is the case of a high thin cloud overlying a brighter thick cloud similar to portions of the image of Fig. 3a (left panel of Fig. 3b). The retrieval using PABSI only spectra is presented in the second panel. The measurements applied to a retrieval algorithm provide useful information about the overlapping cloud layers. Furthermore, these measurements provide the capability of discriminating the presence of a layer of cloud or aerosol over land and snow surfaces that represent difficult conditions of very low contrast.





(b)

Fig. 3a and b. (a) Images of clouds over land and ocean as viewed by MOS (b) example of the retrieval of extinction of high cloud overlying low cloud

3.3 The synergy of active and passive measurements of hydrometeors

The value of combining multi-sensor data for retrieving cloud physical information can be conveniently demonstrated with the following simple example that also underscores the CloudSat observing philosophy. The most basic Level 1 cloud radar product is the radar reflectivity Z, which under certain circumstances, may be approximated as

$$Z \rightarrow \int n(D)\, D^6\, dD \rightarrow N_o\, D^6 \rightarrow wD^3 \quad (1)$$

where D is the particle diameter and n(D) is the cloud drop number density, N_o is the total number concentration and w is the liquid water or ice water content – information of principal relevance to the science goals of CloudSat. Aircraft radar programs developed in support of CloudSat, as well as routine measurement programs like ARM, provide a wealth of information that has advanced our understanding of the reflection characteristics of a large variety of cloud types.

It is well known that reliable estimates of w, however, do not follow directly from measurements of Z alone and additional information about the mean particle size or the relation between mean particle size and w is required. One source of this information comes from cloud optical depth τ that is obtained from measurements of reflected sunlight which relate to w and r_e according to

$$\tau = \int dz \int n(r)\, \pi r^2\, Q_{ext}\, dr \rightarrow \int w/r_e\, dz \rightarrow LWP/r_e \quad (2)$$

where Q_{ext} is the extinction efficiency, r_e is the effective radius and LWP is the liquid (or ice) water path. Additional information can be expected to come from sensors on EOS Aqua.

It follows from (1) and (2) that the radar reflectivity when integrated vertically through the cloud layer, i.e. $IZ=\sum Z$, and optical depth provide independent information about liquid or ice water path (LWP, IWP) and mean particle size, r_e. If we further assume N_0 is constant through the cloud layer (reasonable for low level cloud layers), that it is possible to use IZ, τ and Z to reconstruct the profiles of w and r_e (this is described in more detail in Austin and Stephens (abstract in the same conference proceedings). An example of the retrieval of cloud liquid water content derived in this way from aircraft radar and spectrometer data is provided in Fig. 4 presented as a pdf differences between liquid water content retrieved w measured with *in situ* cloud physics probes.

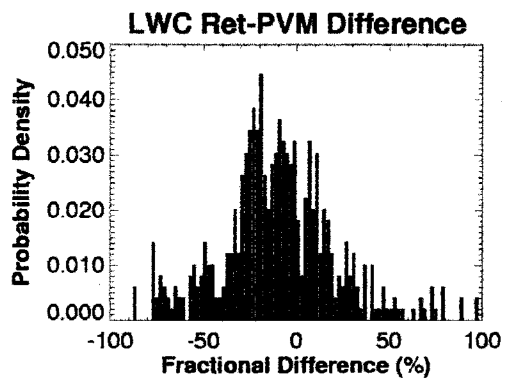


Fig. 4 The difference between retrieved LWC and measured LWC

4.0 Challenges

There remain a number of challenges that have to be addressed as we move toward study of global clouds from space using a milli-metric cloud profiling radar. These challenges will be discussed and the combination of CloudSat observations with EOS Aqua observations represents a unique opportunity to address them.